# SEA ICE FRICTION AND ARCTIC SEA ICE DYNAMICS

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A series of double-shear experiments were undertaken in the Environmental Test Basin at the Hamburgische Shiffbau-Versuchsanstalt (HSVA) in Hamburg. The aim of these experiments was to improve understanding of transient behaviour in sea ice friction. To this end we have fitted our experimental results to a rate- and state- dependent model of friction, which allows us to incorporate non-steady-state behaviour into a relatively simple (three parameter) friction law. In a further series of experiments we investigated the nature of granular flows in sea ice: here we are studying not just two parallel frictional contacts, but an anisotropic array. We have compared the ice tank results to smaller-scale laboratory results and modelling to give insights into applicability to engineering- and basin-scale problems.

## 1. INTRODUCTION

The modern understanding of dry friction begins with Leonardo Da Vinci, and was codified by Amonton and Coulomb in the 17th and 18th centuries. Ice friction is more complicated than dry friction, due to processes of melting and solidifying at the frictional interface, as first interpreted by Bowden and Tabor (1939). Since these beginnings much progress has been made on understanding ice friction, for both freshwater and saline ice (e.g. Oksanen and Keinonen, 1982; Jones et al., 1991; Kennedy et al., 2000; Maeno and Arakawa, 2003). Research has focussed on both empirical determination of friction coefficients, and attempts at physical understanding of the lubrication, freezing, sintering and fracture which control ice friction. However, most large-scale modelling of sea ice processes uses a simple dry friction law, and often the friction coefficient $\mu$ is used as a tuning parameter rather than seen as a physical property (e.g. Hopkins, 1996). In this work we try, by analogy with rock physics, to introduce a simple 3-parameter model which incorporates many of the effects of the complicated physical processes underlying ice friction, but which is simple enough to be easily incorporated into, for example, discrete element models (DEMs) of ice dynamics.

## 2. EXPERIMENTAL SETUP

In order to experimentally measure friction, we use a simple double-shear configuration, with one square moving ice block sandwiched under load between two parallel ice blocks. The scale of the HSVA facility allows us to use a 2m floating block as the central slider, and also allows us to closely mimic typical Arctic conditions, with columnar ice frozen from, and floating on, saline water. Environmental conditions are shown in table 1.

Table 1: Environmental conditions

| | |
|---|---|
| Ice thickness | 0.25m |
| Temperature | -10°C |
| Water Salinity | 33ppt |
| Bulk Ice Salinity | 7.3ppt |
| Ice density | 931 kg m$^{-3}$ |

Figure 1 is a photograph which gives an indication of the scale and configuration of the experiment. The normal load here is provided by hydraulic pusher frames, visible in the bottom left of figure 1. The frictional shear force is provided by a cantilever beam attached to the bottom of a controllable mechanical carriage, visible in the background of figure 1. Both the normal load frames and the shear load beam were fitted with calibrated load cells. The speed at which the ice was pushed was controlled by a relatively crude control on the carriage, but was accurately measured using calibrated displacement transducers. The effective friction coefficient μ is then given as half the shear load divided by the normal load (the factor of two occurs since there are two sliding edges.)

Figure 1: photograph of experimental setup.

## 3. RESULTS

We ran two separate suites of experiments, following a procedure for interpreting transient friction first investigated by Dieterich (1979). Throughout these experiments we use a constant side load of 5kN. In the first group of experiments, we investigate the rate-dependence of ice friction, by pushing the central ice blocks at a variety of constant speeds. At low speed (1-10 $mms^{-1}$), stick-slip friction is often observed, while at higher speeds the motion is smooth. These results show some experimental scatter, but overall a log-linear fit of friction to speed can be made, as shown on the LHS of figure 2. We note that this log-linear fit is somewhat simplistic compared to, e.g. the multi-regime interpretation of Hatton et al (2009): but simplicity is our aim. In the second group of experiments we hold the central slider still under normal load for a series of 'hold time' ranging from 10 to 1000 seconds, and then investigate the friction spike on the resumption of motion. The values of this friction spike are shown on the RHS of figure 2.

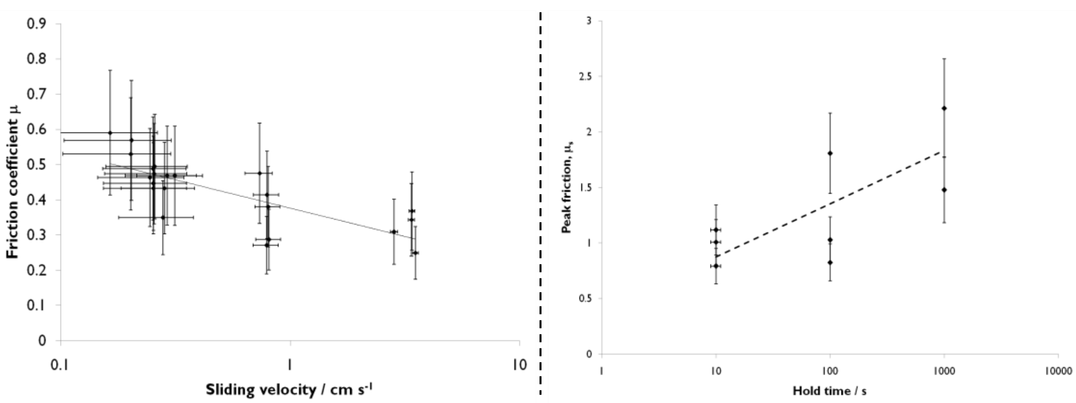


Figure 2: an experimental determination of the rate-dependence of friction (L) and of the peak friction coefficient on resumption of sliding following a static contact under load (R).

Following the methodology of Dieterich (1979) for rock friction, and the interpretation of Ruina (1983), we can then combine these results into a single rate and state model of ice friction, in which a single state variable is introduced to cover the various physical processes, discussed above, which lead to memory effects in friction. An explanation of this model, and our empirically determined parameter values, are given in Lishman et al. (2009). We find that this model successfully predicts non-steady-state behaviour during cyclic-velocity sliding in laboratory experiments (Lishman et al., in prep.)

## 4. FURTHER WORK

While these double shear experiments provide useful and quantifiable information on the nature of sea ice friction, the overall aim of the project is to better describe sea ice dynamics on aggregate. To this end we have also undertaken a series of experiments looking at ensemble flows of small (~50cm) diamond shaped floes, with the aim of representing the anisotropy observed in satellite imagery of the Arctic. In particular, we are interested in quantifying the edge-edge sliding between floes (the frictional dissipation in this sliding can be represented by the rate and state model described above.) This work is ongoing, but figure 3 shows the configuration in the ice tank and in a discrete element model of the same.

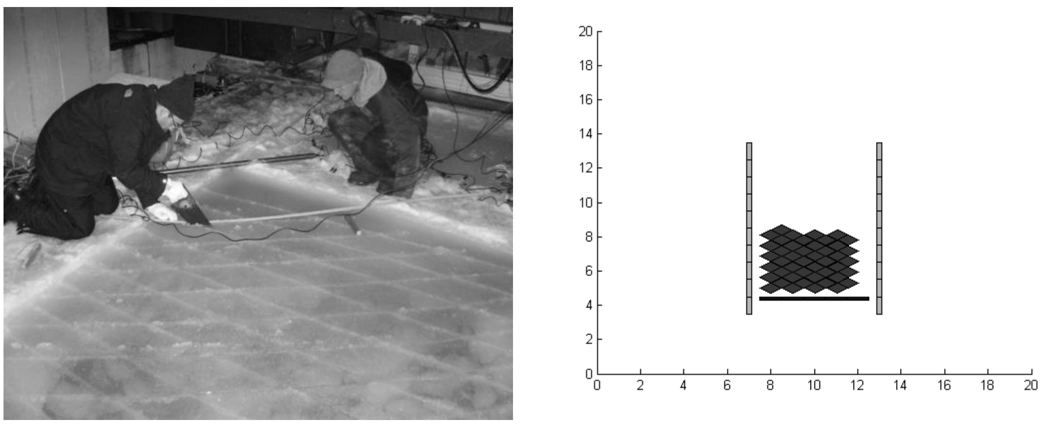


Figure 3: granular flows, in the ice tank (L) and in a discrete element model (R).

## 5. CONCLUSIONS

We have undertaken a series of large-scale ice friction experiments in the Environmental Test Basin at HSVA. These experiments provide us with a full set of parameter values for a rate and state model of ice friction, which allows transient memory effects to be incorporated into friction laws for large-scale modelling without a great increase in complexity.

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